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Abstract: Numerous climate proxies from across Central, South and East Asia have yielded different ages for the start or intensification of a monsoon climate system. Common estimates include the early part of the early Miocene (~23-20 Ma) and the late Miocene (~11-8 Ma). In the early Miocene the average position of the Intertropical Convergence Zone (ITCZ) was likely to be the >2000 km closer to the Himalaya than at present (based on published data for the palaeolatitude of the Central Pacific ITCZ), such that Himalayan climate was marked by high precipitation, but not necessarily seasonality. Here we propose that increased seasonality in the late Miocene in the Himalaya and neighbouring regions was a response to an increase in the distance between the ITCZ and the Himalaya/Tibet, such that the ITCZ was only brought northwards during the northern hemisphere summer each year. This is essentially the pattern of the modern South Asian monsoon system. These climatic changes coincide with a switch from north-south extensional shear on the northern side of the High Himalaya, thrusting on the Main Central Thrust and rapid metamorphic exhumation, to thrusts further south in the Himalaya (Main Boundary Thrust) and a reduction in High Himalayan exhumation rates. We speculate that the tectonic changes were at least in part a response to a reduction in precipitation over the High Himalaya: the Himalayan thrust belt re-organised to maintain a critical taper appropriate to a drier orogen. The reduction in metamorphic exhumation after the early Miocene would also have led to a reduction in the flux of metamorphic CO_2 to the atmosphere, thereby promoting the global shift to a cooler climate in the mid Miocene.

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Reconciling the Intertropical Convergence Zone, Himalayan/Tibetan tectonics, and the onset of the Asian monsoon system

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ABSTRACT

Numerous climate proxies from across Central, South and East Asia have yielded different ages for the start or intensification of a monsoon climate system. Common estimates include the early part of the early Miocene (~23-20 Ma) and the late Miocene (~11-8 Ma). In the early Miocene the average position of the Intertropical Convergence Zone (ITCZ) was likely to be the >2000 km closer to the Himalaya than at present (based on published data for the palaeolatitude of the Central Pacific ITCZ), such that Himalayan climate was marked by high precipitation, but not necessarily seasonality. Here we propose that increased seasonality in the late Miocene in the Himalaya and neighbouring regions was a response to an increase in the distance between the ITCZ and the Himalaya/Tibet, such that the ITCZ was only brought northwards during the northern hemisphere summer each year. This is essentially the pattern of the modern South Asian monsoon system. These climatic changes coincide with a switch from north-south extensional shear on the northern side of the High Himalaya, thrusting on the Main Central Thrust and rapid metamorphic exhumation, to thrusts further south in the Himalaya (Main Boundary Thrust) and a reduction in High Himalayan exhumation rates. We speculate that the tectonic changes were at

least in part a response to a reduction in precipitation over the High Himalaya: the Himalayan thrust belt re-organised to maintain a critical taper appropriate to a drier orogen. The reduction in metamorphic exhumation after the early Miocene would also have led to a reduction in the flux of metamorphic CO_2 to the atmosphere, thereby promoting the global shift to a cooler climate in the mid Miocene.

Keywords: Intertropical Convergence Zone, Himalaya, Cenozoic, climate, monsoon.

1. Introduction

In a recent paper (Armstrong and Allen, 2011) we argued that the changing palaeolatitudes of the Intertropical Convergence Zone (ITCZ) and the Himalaya had an important control on the Asian climate during the late Cenozoic. The specific argument was that the latitudes of the ITCZ and the Himalaya were >2000 km closer in the early Miocene (~20 Ma) than they are today, such that the range would have received precipitation on a scale equivalent to the modern South Asian summer monsoon (roughly June-September) all through the year. This hypothesis is based on reconstructions of the Pacific ITCZ (Lyle et al., 2002) and the northward drift of the Indian plate (Molnar and Stock, 2009). The consequences of this proximity in the early Miocene would have been high erosion rates, consistent with the exhumation data for the range for this time (White et al., 2002), and possibly even the development of “channel flow” tectonics (Beaumont et al., 2001; Searle, 2010) and the generation of crustal melt leucogranites (Harris, 2007).

In this review we develop this hypothesis to address 1) why different climate proxies have produced different ages for the onset of the Asian monsoon system, and

2) in particular, why many results from both north and south of the Himalaya/Tibet indicate a late Miocene onset or intensification age. Our conclusion is that in the late Miocene the increasing divergence of the ITCZ and the Himalaya enhanced seasonality within the range and to its south, whilst overall precipitation declined.

2. Miocene Himalayan/Tibetan tectonics and palaeoaltitudes

As many authors have produced reviews of Himalayan/Tibetan tectonics (e.g. Harrison et al., 1992; Yin and Harrison, 2000; Hodges, 2000; Yin, 2006; Yin, 2010) we do not provide a detailed account, but summarise Miocene events. The Miocene epoch began long after the commonly-assumed initial collision at ~50 Ma (e.g. Dupont-Nivet et al., 2010), such that it is a long-standing issue how and where plate convergence was accommodated for the first 30 million years of collision (the “Eohimalayan” phase of tectonics; Hodges, 2000). Increasing evidence is emerging for deformation and consequent uplift and exhumation through this time (Najman et al. 2008; Aikman et al. 2008), but it is still scant.

The early Miocene interval was a time of dramatic change, with the initiation of the South Tibetan Detachment System (STDS) and the Main Central Thrust (MCT) within the Himalaya (Burchfiel et al., 1992; Hodges et al., 1998; Searle et al., 2008; Kellett et al. 2009). Rapid exhumation of rock in the intervening wedge in the High Himalaya was associated with the generation of leucogranite via decompression (Harris and Massey, 1994; White et al., 2002). The most rapid exhumation, leucogranite generation and ductile shear all took place in the early Miocene and diminished in the middle-late Miocene (see Catlos et al., 2004), with some evidence for diachroneity from west to east along the range (Harris, 2007). For example, Searle et al. (1999) noted that in the Zanskar region of the High Himalaya (Fig. 1), exhumation rates dropped from 6-10 mm/yr between 21 and 18.5 Ma to 0.4 mm/yr afterwards. The distinctive early Miocene tectonics of the Himalaya has led to the development of channel flow models for the mid and lower crust (Beaumont et al., 2001), although some authors see the synchronous extensional and thrust-sense shear as the readjustment of a critically-tapered orogenic wedge (Robinson et al., 2006; Kali et al., 2010).

At roughly the time activity on the MCT and STDS declined in the middle Miocene, normal faulting started in southern Tibet, indicating rough east-west extension rather than the top-to-north extensional shear on the STDS (Molnar and Tapponnier, 1978). The age constraints on this younger normal faulting are patchy, such that it is not possible to get a clear picture of it through space and time, or its relations to the STDS. The oldest ages found so far for faulting are 14 Ma (Coleman and Hodges, 1995) and 13.5 Ma (Blisniuk et al., 2001), i.e. middle Miocene. Faulting is active (Molnar and Tapponnier, 1978; Molnar and Lyon-Caen, 1989). North-south dykes in southern Tibet, dated at 18.3 ± 2.7 Ma, have been taken to mean east-west extension at this time (Williams et al., 2001; Fig. 1), but this does not necessarily mean contemporary normal faulting: $\sigma 3$ could be oriented east-west, in a constrictional stress field. The north-south Dinggye normal fault cross-cuts the STDS, and began its motion >11 Ma (Leloup et al., 2010). See Maheo et al. (2007) for a contrary view, suggesting that normal faulting in southern Tibet is mainly a Pliocene-Quaternary phenomenon.

One explanation for the onset of the east-west extension is partial loss of the lower continental lithosphere, with resultant surface uplift following isostatic readjustment (Houseman et al., 1981; England and Houseman, 1989; Molnar et al., 1993). However, this is difficult to reconcile with palaeoaltitude reconstructions that place southern and central Tibet at close to their present elevations by 15 Ma or earlier. Most of these studies are based on carbonate $\delta^{18}O$ values. The pattern is emerging that southern and central Tibet has been at or close to present day elevations through the Neogene at least (Garzione et al., 2000; Rowley et al., 2001; Rowley and Currie, 2006; DeCelles et al., 2007; Fig. 1), and possibly once higher than at present (Murphy et al., 2009; Saylor et al., 2009). Another approach was taken by Spicer et al. (2003), who used fossil leaf analysis to infer that southern Tibet has been close to its present elevation since 15 Ma. Lithosphere loss is not confirmed by recent estimates of plate thickness, based on earthquake shear wave velocity gradients (Priestley and McKenzie, 2006), which show a >200 km thick "core" under Tibet. Therefore an alternative to lithosphere detachment/delamination models may be necessary. Cook and Royden (2008) modelled extension in southern Tibet as the result of eastward crustal flow towards the southeast plateau corner, without requiring significant change in plateau surface elevation in southern Tibet. Evidence for middle Miocene surface uplift (~ 15-10 Ma) has been found in southeast Tibet and the Longmenshan (Clark et al., 2005; Ouimet et al., 2010), based on fission track and (U-Th)/He dates from fluvial gorges (Fig. 1). Fluvial incision further north along the east side of Tibet appears to have begun later, at ~6 Ma (Kirby et al., 2002). This is consistent with the model of Cook and Royden (2008), without being conclusive proof.

Middle and late Miocene Himalayan thrusting focused to the south of the MCT, in particular the Main Boundary Thrust and the Main Frontal Thrust (Schelling, 1992; Meigs et al., 1995; Lave and Avouac, 2000; Huyghe et al., 2001; Herman et al., 2010). Present day surface deformation in the Himalaya is focussed along the front of the range. The structure of the Himalaya is also marked by pronounced syntaxes at its western and eastern ends, named after the mountains of Nanga Parbat and Namche Barwa respectively. Both of these regions show extremely high rates of exhumation during the Pliocene-Pleistocene (Zeitler et al., 1993; Seward et al, 2008), but both show evidence for an origin as far back as 10 Ma (Treloar et al., 2000; Booth et al., 2009).

3. Monsoon climate records

The modern Asian monsoon climate is marked by two main characteristics: seasonally reversing winds and heavy summer rainfall. The South and East Asian monsoons have different timings, characteristics and dynamics (Molnar et al., 2010). The South Asian monsoon affects the region south of the Himalaya and also Indochina and the South China Sea. Peak rainfall is from June-September. The East Asian monsoon affects China and adjacent countries to its east. Winters are not generally as dry as regions affected by the South Asian monsoon, and heavy summer rainfall arrives somewhat earlier. Tibet and the Himalaya may drive both forms of the monsoon, but in different ways (Boos and Kuang, 2010; Molnar et al., 2010). The high topography may act as a heat source, or a barrier to southward air flow, in either mechanism creating the South Asian monsoon by bringing a northward flow of tropical air in the northern hemisphere summer. The East Asian monsoon may result more from the Tibetan plateau blocking the subtropical jet stream, which passes south of Tibet in winter and north in summer.

The modern Asian summer monsoon involves the northward movement of the Intertropical Convergence Zone over the Indian subcontinent and neighbouring areas of South Asia (Fig. 2), partly because it tracks the solar zenith through the year, but mainly because it is drawn northwards by a zone of low atmospheric pressure over northern India, the Himalaya and Tibet (Ruddiman and Kutzbach, 1989). Regardless of whether the dominant mechanism is heating of the overlying atmosphere or blocking the southward flow of cool air (Boos and Kuang, 2010), the Himalaya and Tibet are primary influences on atmospheric circulation patterns and hence climate. For this reason the surface uplift history of the Himalayan-Tibetan orogen has been suggested to be closely linked to the development of the Asian monsoon (Molnar et al., 1993; Clift et al., 2008), with feedbacks operating in both directions. A higher, wider Tibetan plateau would have intensified the monsoon, while a wetter climate would have increased erosion rates in the Himalaya, in turn influencing relief and exhumation patterns (e.g. Kutzbach et al., 1989). Late Cenozoic surface uplift and erosion of the Himalaya and Tibet have been linked to global climate change, via high chemical weathering rates and organic carbon burial, causing a drawdown of atmospheric CO_2, and hence global cooling (Raymo et al. 1988; Raymo and Ruddiman, 1992). Increasing seawater strontium isotope values in the late Cenozoic are interpreted as reflecting increasing erosion of the Himalayan-Tibetan system (Fig. 3a; Richter et al., 1992).

No consensus exists for the timing of initial monsoon development or intensification. Proposed ages cluster in the early Miocene (~22-20 Ma; e.g. Guo et al., 2002), middle Miocene (16-11 Ma; e.g. Clift et al., 2004) and late Miocene (11-8 Ma; e.g. Molnar et al., 1993), although middle Miocene ages (Clift et al., 2004) may be viewed as the peak of conditions which originated in the early Miocene (Clift et al., 2008). The locations of sites that have provided data, and inferred ages, are shown in Fig. 1. Table 1 summarises these observations. We do not refer to the numerous records of climate change in the Pliocene-Quaternary, although these have been argued as evidence for rapid tectonic change in the Himalaya and/or Tibet. Refer to Molnar (2005) and Molnar et al. (2010), who succinctly showed the flaws in the idea.

3.1. Early Miocene ages

Many of the studies relevant to the timing of the onset of the Asian monsoon system are derived from data collected at one or several localities, with necessary extrapolation to regional scales. Sun and Wang (2005) presented a different approach, by collating “palaeophytogeographical patterns” across the whole of China. Their results show a shift from an east-west arid belt across China in the Paleogene to a Neogene pattern of aridity restricted to northwest China, similar to the present day. The transition occurred close to the Oligocene-Miocene boundary, but is not precisely datable because of the broad resolution of the study.

Early Miocene ages are also drawn from loess deposits close to the Liupan Shan in northern China (Fig. 1), which record alternations between the loess itself and paleosols as far back as 22 Ma (Guo et al., 2002). The loess is interpreted to result from dust derived from northerly winds during the winter monsoon (although at the present day much more dust is generated in the Spring: Roe, 2009), while the paleosols represent wetter intervals influenced by the summer monsoon. Therefore the loess record provides good evidence for seasonality, but not necessarily for enhanced humidity. A record of humid early Miocene climate is provided by pollen data from fluviolacustrine sediments from the same region (Jiang and Ding, 2009), dating from 20 to 0.08 Ma. The assemblages are generally dominated by steppe flora throughout the Neogene and Quaternary, but variations between the proportions of *Artemisia,* more halophytic taxa such as *Humulus,* and deciduous broad-leaved trees such as *Juglans,* are interpreted by Jiang and Ding (2009) to mean a relatively humid climate from 20.13 to 14.25 Ma (i.e. early Miocene to early middle Miocene), influenced by the East Asian summer monsoon. This was followed by a significant decline in the summer monsoon and a more arid climate from 14.25 to 11.35 Ma. There has been a relatively arid climate and weak summer monsoon ever since. Further west, but still in the north Tibetan region (Qaidam Basin; Fig. 1), a shift to wetter conditions in the early Miocene was inferred by Wang et al. (1999) on the basis of pollen assemblages and a decrease in the proportion of xerophytes near the Oligocene-Miocene boundary.

The onset of aeolian deposition within the interior of the Junggar Basin began at ~24 Ma, i.e. just before the Oligocene-Miocene boundary (Sun et al., 2010; Fig. 1), suggesting that the modern system of westerly winds in this area began at this time. Dust was supplied to the Junggar Basin from Central Asia, in contrast to the northerly winds that supply the Chinese loess plateau.

Sedimentary $\delta^{18}O$ and $\delta^{13}C$ data from the northern side of the Tibetan plateau show a Neogene increase in both $\delta^{18}O$ and $\delta^{13}C$ values (Kent-Corson et al., 2009), interpreted as a climatic shift to more arid conditions and basin isolation. The trends vary between localities, such that some places show no clear pattern through the Noegene and others have abrupt shifts that might indicate climatic change in the middle or late Miocene. The $\delta^{18}O$ and $\delta^{13}C$ records of Rieser et al. (2009) in the Qaidam Basin show no clear overall trends.

Chemical and mineralogical proxies have been used to infer enhanced monsoon climate, on the basis that runoff is a principal control of chemical weathering rates. Wei et al. (2006) and Clift et al. (2008) applied this approach to sediments in the South China Sea (ODP site 1148; Fig. 1), derived from the Pearl River drainage basin. This river system was affected by Asian monsoon climate, but not by high elevation source areas that would also carry a record of enhanced physical erosion related to surface uplift of the Himalaya and Tibet. Clift et al. (2008) showed a trend of gradually increasing chemical weathering (and hence inferred precipitation) from 24 to 10 Ma. Chemical weathering rates declined between 10 and 3.5 Ma, and rose thereafter. Indices from the Indus and Bengal fans (Fig. 1) show similar patterns, with the caveat that the physical erosion record of the Himalaya must be present in both fans.

The combination of high precipitation and mountainous relief should produce high erosion rates, ultimately recorded as high sedimentation rates in basins at the end of sediment routing systems. Assuming greater Asian monsoon intensity to be expressed by higher precipitation rates, this should feed through to greater accumulation rates in basins with the accommodation space to receive the sediment. Clift and Gaedicke (2002), Clift (2006) and Clift et al. (2008) found high sediment flux rates for the Indus fan (Fig. 1), which receives detritus from the Himalayan/Tibetan orogen, in the early and middle Miocene, followed by a decrease in the late Miocene. Bengal fan records are less complete, but chemical weathering indices show a relatively wet climate in the sediment source area for ODP Site 718 in the late early and middle Miocene, with a shift to inferred drier climate at 8-7 Ma (Clift et al., 2008). These results were interpreted by Clift et al. (2008) to mean an Asian monsoon climate in operation since the early Miocene. From a similar approach Clift et al. (2004) found peak sedimentation rates offshore of the Mekong drainage system beginning in the early Miocene, somewhat earlier than many basins on the East Asian margin (Fig. 1).

In summary, there are now many indicators of South and East Asian climate change in the early Miocene, consistent with the onset or intensification of climatic conditions akin to the modern range of climates (Table 1; Fig. 3b). A note of caution is needed when interpreting these changes in terms of monsoon intensification: the early Miocene was generally a warm, and presumably humid, time on a global scale (e.g. Zachos et al., 2001), such that increased humidity in South or East Asia may not simply be a regional climatic change.

3.2. Middle Miocene ages

There are studies that claim climatic shifts in the middle Miocene (16-11 Ma), largely derived from high sedimentation rates in East Asian basins (e.g. Clift et al., 2004), but the emphasis is now towards a monsoonal climate at this time being a continuation from early Miocene times (Clift et al., 2008), with high global sediment fluxes being influenced by climatic instability, specifically the shift from the early middle Miocene Climatic Optimum to colder conditions (Zachos et al., 2001; Clift, 2010; Fig. 3a).

High middle Miocene sedimentation rates in the Indus fan and Arabian Sea were interpreted by Clift and Gaedicke (2002) and Clift et al. (2008) as indicating monsoonal conditions in the sediment source areas of the Himalaya and Tibet, continuing or even intensifying from an early Miocene onset. Similar enhanced sedimentation rates were found by Clift et al. (2004) from basins along the East Asian continental margin, and Burma (Fig. 1). However, other authors have inferred increased aridity in the Himalaya and Tibet from the middle Miocene. For example, Wei et al (2006) and Wan et al (2007) noted decreases in the degree of chemical weathering of sediment delivered to the South China Sea, that they attributed to increased aridity in Asian sources areas at about 16-15 Ma. Further increases in aridity were inferred for about 8 Ma and 3 Ma. Neogene pollen records from across China also indicate a shift towards a drier climate in the mid part of the middle Miocene (14.25 to 11.35 Ma), with a decrease in the strength of the East Asian summer monsoon (Jiang et al., 2008; Jiang and Ding, 2009). A decrease in the East Asian summer monsoon was also deduced from 12 Ma, in the Sikouzi section, northern China, based on grain-size analysis of windblown sediments (Jiang and Ding, 2010). The increase in the 10-70 μm fraction was interpreted to mean a much stronger winter monsoon at this time.

Lacustrine carbonate isotopic records for a long (29 Myr) sedimentary record in the Linxia Basin, on the northeast side of Tibet (Fig. 1) show stability in climate from 29-12 Ma, with carbonate $\delta^{18}O$ at roughly -10.5‰, with a switch to more arid conditions at 12 Ma ($\delta^{18}O$ at -9‰) that essentially continued through to Pliocene times (Dettman et al., 2003). These authors interpreted 12 Ma as the time at which the Tibetan plateau grew high and wide enough to cause a significant rain shadow in this part of Tibet.

Within the Himalayan foreland in northern Pakistan, Zaleha (1997) found paleosols consistent with a warm, humid climate in the middle Miocene. There was also evidence for pronounced seasonality, in the form of alternations between nodular calcite horizons and iron oxide nodules. The former are evidence for a marked dry season, the latter for a wet season. Therefore the combination and alternation suggests monsoonal conditions similar to the present day.

In summary, high sedimentation rates in many South and East Asian basins are possible evidence for rapid erosion and presumably high precipitation rates by the middle Miocene (Clift et al., 2004). It is not clear if these conditions began at this time or were enhanced, and to what degree they relate to global climatic instability (Clift, 2010) rather than tectonic changes in the Himalaya and Tibet. There is some evidence that a monsoon climate was in operation south of the Himalaya during the middle Miocene, to produce both high precipitation rates and seasonality (Zaleha, 1997). However, other studies suggest an increase in aridity in East Asia at this time (Wei et al., 2006; Wan et al., 2007).

3.3. Late Miocene ages

As many proxy data are now available to suggest early and middle Miocene monsoon climates in south and east Asia, as summarised above, it is notable how many datasets imply climatic change in the late Miocene (11-5 Ma), particularly in the first half of the sub-epoch (Table 1; Fig. 3b). late Miocene ages include localities to the south of the Himalaya, either in deposits of the Himalayan foreland or further south in the Arabian Sea. But there are more widespread localities with changes at this time, including the South China Sea and the loess-paleosol succession of north and northeast China.

Pedogenic carbonate stable isotopes (carbon and oxygen) have proven to be very useful climate proxies within the syn-orogenic deposits associated with the Himalaya and Tibet. Quade et al (1989) documented late Miocene shifts in $\delta^{13}C$ and $\delta^{18}O$ towards more positive values from northern Pakistan (Fig. 1). The change in $\delta^{13}C$ was on the order of 10‰ in 2 Myr, and for $\delta^{18}O$, ~3‰. This change began at 7.5 – 8 Ma for the $\delta^{13}C$ shift (using the Cande and Kent (1995) magnetic polarity timescale), and slightly earlier for $\delta^{18}O$. Quade et al. interpreted the $\delta^{13}C$ results as recording the shift from C_3 to C_4 type vegetation, i.e. forest to grassland, given that plant-respired CO_2 is the main source of carbon in pedogenic carbonate, and C_3 vegetation has more negative $\delta^{13}C$ than C_4 vegetation. The spread of C_4 grasslands is in turn taken to represent onset of strong monsoon conditions in the region, because it implies seasonal drought that does not favour forest – even though total rainfall would normally be less than that required to support forest in the same area. Harrison et al. (1993) and Quade et al. (1995) found a similar shift in $\delta^{13}C$ in pedogenic carbonates from southeast Nepal, at 7 Ma (Fig. 1). Quade et al. (1995) also reported a positive shift in $\delta^{18}O$ of ~4‰ from the Nepalese sections, occurring at ~6 Ma, i.e. about 2 Myr younger than in Pakistan. Precipitation $\delta^{18}O$ and hence soil carbonate $\delta^{18}O$ is controlled by several factors, including the amount of precipitation, evaporation and the elevation of the source areas. It is not clear what controls these positive shifts, but an increase in precipitation would normally mean a decrease in $\delta^{18}O$ values while an increase in evaporation would cause an increase in $\delta^{18}O$ values. Therefore the results might be consistent with an increase in aridity and/or seasonality, but not an overall increase in precipitation.

Increases in $\delta^{13}C$ and decreases in $\delta^{18}O$ values of soil carbonate nodules from the Himalayan foreland basin in India were interpreted by Sanyal et al. (2004) to indicate i) a switch from C_3 to C_4 type vegetation, and ii) monsoon onset by 6 Ma, with a possible earlier peak at 10 Ma. Note that the decrease in $\delta^{18}O$ is in the opposite direction to the results of Quade et al. (1989) and Harrison et al (1993), such that both sets of authors use their results to indicate monsoon intensification at about the same time, but for very different reasons. Galy et al. (2010) noted an increase in $\delta^{13}C$ for organic matter in the Bengal fan at 7.4 Ma, also consistent with a change to C_4 type vegetation in the sediment source areas.

Dettman et al. (2001) used $\delta^{18}O$ trends in freshwater bivalve shells and mammal teeth to study seasonal variation in Himalayan foreland surface waters in the late Miocene and Pliocene. The rather limited change in values over this period was used to infer a strong Asian monsoon from 10.7 Ma, with the implication that the Tibetan plateau was high and wide enough through this time to create a monsoon system similar to the present day. Wet-season rainfall was significantly more negative (-9.5‰) before 7.5 Ma than afterwards (-6.5‰). This could be evidence for increased aridity from 7.5 Ma.

The isotopic shifts from the Himalayan foreland are supported by palaeontological evidence from the same region. Vertebrate palaeontology studies were at the forefront of evidence for climatic change near the Himalaya in the late Cenozoic. Flynn and Jacobs (1982); Barry et al. (1985) and Barry (2002) used changes in rodents and larger herbivores to infer a shift towards grassland habitats in northern Pakistan by ~7 Ma. This is supported by the fluvial sedimentology of the host strata for these fossils, which shows a change to a more seasonal discharge and increased aridity (Barry et al., 2002). Fossil leaf and pollen show a transition from forest to grassland in central Nepal at ~8 to 6.5 Ma (Hoorn et al., 2000).

Sedimentary records from the western Arabian Sea provide evidence for increased seasonality around 8 Ma, attributed to strengthening monsoon winds and increased upwelling in this region (Kroon et al., 1991; Prell et al., 1992). The key data point is the increased component of the planktonic foraminifer *Globigerina bulloides* in the sediment at this time, jumping from a few percent of the annual mass accumulation to tens of percent. *G. bulloides*, a subpolar species, flourishes in monsoon wind induced-upwelling in the coastal waters of the tropics like the NW Arabian Sea, making it an effective proxy for seasonality in this region, although not necessarily a gauge of which wind system is the stronger, summer or winter.

Loess records from northern China have provided support for a climate change in the late Miocene, and the appearance of such deposits may be taken as evidence for the establishment of wind systems close to the modern regime, influenced by the East Asian monsoon. Qiang et al (2001) derived a magnetostratigraphic age of 8.35 ± 0.05 Ma for the base of aeolian red clay beneath the Plio-Pleistocene loess-paleosol succession at Jiaxian, northern China (Fig. 1). These deposits are heavily modified by pedogenesis, and suggest a warm and humid climate developed at this time. Xu et al. (2009) have recently taken the eastern loess record back to 11 Ma, based on magnetostratigraphy. A pulse of aeolian dust in the North Pacific at ~8 Ma was recorded in sediments from ODP site 885/886 (Rea et al., 1998), interpreted as transported by stronger westerlies from northeast Asia, thereby strengthening the case for increased dust production within northern China at this time.

Saylor et al. (2009) used isotope data from molluscs and plants from the Zhada Basin, southwest Tibet (Fig. 1), to infer a cold, arid climate similar to the modern since ~9 Ma, but with a shift from C_3 to C_4 type vegetation. Palaeoaltimetry estimates suggested a drop in elevation of ~1.5 km in this time. These results indicate no late Miocene climate change, but a change in vegetation patterns that presumably results from other causes. Fan et al. (2007) studied $\delta^{18}O$ records of Neogene deposits of the Linxia Basin (Fig. 1), aged between 13.1 and 4.3 Ma. Between 13.1 and 8 Ma, strong oscillations between dry and wet conditions were inferred from fluctuations in the $\delta^{18}O$ records, and interpreted as changes from hydrographically closed and open lake systems. A short-lived arid pulse took place from 9.6 to 8.5 Ma. After ~8 Ma, the climate was more stable, less arid and the lake system was hydrographically open. Cooler and/or drier conditions prevailed from 5.3 Ma.

Zheng et al (2004) found a decrease of the abundance ratio of planktonic foraminifera *Globigerinoides sacculifer/G. ruber* and increase of *Neogloboquadrina* at ~8 Ma at ODP site 1146 in the South China Sea, which they interpreted as a lowering of the sea surface temperature and increased productivity, related to an intensification of East Asian winter monsoon winds and upwelling. Steinke et al. (2010) have recently examined temperature independent variations in seawater $\delta^{18}O$ (i.e. a proxy for sea surface salinity) for the ODP site 1146 using a combined approach of planktonic foraminiferal Mg/Ca ratios and $\delta^{18}O$ analysis. They found that local seawater $\delta^{18}O$ increased (became heavier) by 0.34‰, interpreted as a sharp reduction in the East Asian summer monsoon intensity at ~7.5 Ma. This is consistent with results of Wan et al (2007) and Wei et al (2006) who studied shifts in chemical weathering patterns of detrital sediment derived from southeast Asia (within the South China Sea), and interpreted an intensification of the winter monsoon and a decline in the summer monsoon at ~8 Ma.

Sediment flux records for the late Miocene commonly show a decline for regions sourced from the Himalaya and Tibet, in contrast to the increase expected if the monsoon intensified at this time (Burbank et al., 1993; Clift et al., 2008). Such flux reductions are true of both the Indus and Bengal fans (Burbank et al., 1993; Clift et al., 2008), which are major recipients of Himalayan and Tibetan sediment.

Inferred climatic changes in Asia at 10-8 Ma have to be put in a global context. There is evidence from the Indian, equatorial Pacific and southern Atlantic oceans of a biogenic bloom in the late Miocene – early Pliocene (Farrell et al., 1995; Dickens and Owen, 1999). Gupta et al (2004) reported a major increase in biogenic productivity in the eastern Indian Ocean at 10-8 Ma, based on the establishment of benthic biofacies that indicate a year-round high flux of organic matter from the sea surface to the ocean floor. They suggested that the oceanic high productivity occurred across a larger region than that affected by the Asian monsoons or detritus produced by monsoonal climate, and that increased upwelling driven by strengthening wind systems was a more likely cause, itself created by high-southern-latitude cooling and increased ice volume.

4. Changing latitudes of the ITCZ and the Himalaya

We reviewed the evidence for the palaeolatitude of the ITCZ in the Pacific in Armstrong and Allen (2011) and so only summarise the data here (Fig. 3c). Different lines of evidence used include the position of the smectite-illite transition (because this marks the boundary between wind-blown clay derived predominantly from Asia and from Central/South America; Lyle et al., 2002), and the composition of manganese crusts (because this changes depending on changing biologic and detrital fluxes) (Kim et al., 2006; Hyeong et al., 2005). Both sets of records indicate that the mean position of the ITCZ has moved southwards in the Neogene. Differences in latitudes between the Central and Western Pacific are consistent with present day variation, with Western Pacific palaeolatitudes consistently lying closer to the equator.

Himalayan palaeolatitudes are hard to know precisely, given that the overall plate convergence of India and Eurasia has been partly taken up in the range (perhaps 1000 km out of 2500 km total convergence), making the exercise more difficult than tracking the relative motion of stable plate interiors. There is no single set of values that represents the whole of the Himalaya. Molnar and Stock (2009) calculated palaeo-positions for two localities on the northwest and northeast side of the Indian plate. Armstrong and Allen (2011) added 500 km to the latitude of these points for each time, to more closely represent the Himalayan palaeolatitudes – with the caveats about the "concertina" effect of Himalayan thrusting just noted. These positions are plotted on Fig. 3c alongside the Pacific ITCZ values. As Armstrong and Allen (2011) discussed, the early Miocene (~20 Ma) latitudes of the Central Pacific ITCZ and the Himalaya were over 2000 km closer than at present, and may have overlapped, at least in the northwest Himalaya. Here, we note the degree of divergence by 10 Ma. The palaeolatitudes had separated: the Central Pacific ITCZ had migrated ~1500 km south of its early Miocene position (Lyle et al., 2002) and the northern margin of the Indian plate/Himalaya had migrated northwards, probably by 200-400 km (Molnar and Stock, 2009).

5. Discussion and conclusions

The above review demonstrates that there are abundant data to indicate Asian monsoon intensification in both the early and late Miocene. If the question is strictly "when did a monsoon system begin?" the answer appears to be the early Miocene. Data from this timeframe indicate many of the climatic characteristics associated with the modern monsoon: high erosion rates from the Himalaya (attributed to high precipitation); climatic seasonality (related to the shift in wind direction between summer and winter); palaeobotanical evidence for humid climate through eastern China (consistent with the range of the modern East Asian summer monsoon); loess deposition in northern China (equivalent to the modern dust blown in to this region from further north). Given that the early Miocene time period is roughly 30 million years after initial India-Eurasia collision, it follows that a threshold was crossed at this time to trigger the monsoon in both its Indian and East Asian versions. There was plausibly a combination of the lateral and/or vertical growth of the Himalaya and Tibet (Tapponnier et al., 2001; Harris, 2007), the convergence of the ITCZ and the

Himalaya (Armstrong and Allen, 2011), drying of Paratethys across central Asia (Ramstein et al., 1997) and transgression across the East Asian continental margin (Zhang et al., 2007).

The Early Miocene was globally a time of relatively warm, humid climate (e.g. Zachos et al., 2001), albeit punctuated by Antarctic glaciations (Miller et al., 1991). Amongst other possible mechanisms, this mild global climate would have been promoted by high rates of combined metamorphism and exhumation in the Himalayas, via rapid fluxes of metamorphic CO_2 to the atmosphere (applying the reasoning of Becker et al., 2008; Skelton, 2011). The decrease in Himalayan metamorphism and exhumation rates in the middle Miocene would presumably have reduced this CO_2 flux, at the time the global climate swung in to a colder mode.

This leaves the question of the significance of climatic changes reported or inferred for ~8 Ma. Molnar et al. (1993) proposed a correspondence between tectonic events in the Himalayan/Tibetan system at roughly this time and the climatic changes in Asia. In this model increased surface elevations of the Tibetan plateau, perhaps caused by partial loss of the lower lithosphere, would lead to an intensified monsoon system whether this was related to the physical barrier presented by the elevated topography or the increased heating of the atmosphere (Molnar et al., 2010). Increased seasonality at ~8 Ma fits this scenario, whether it is interpreted from the marine sedimentary record (Kroon et al., 1991) or terrestrial deposits (Quade et al., 1989; An et al., 2001). However, the evidence for lithosphere loss and surface uplift at 8 Ma is now debatable (Molnar, 2005), as described above, which casts doubt on the model.

Also, the story at 8 Ma appears more complex than a simple, regional intensification of the monsoon in all of its forms. Sedimentation rates in the basins receiving Himalayan detritus record a slow down in the late Miocene (Clift et al., 2008). Multi-isotope (Sr, Nd and Os) were used as proxies for the source of the sediments deposited in the Bengal Fan over the last 12 million years by Galy et al. (2010), and their data indicated a stable provenance over this time, without evidence for changing drainage or uplift histories. Biological productivity increased in the Atlantic, Pacific and Indian oceans far away from the influence of these Himalayan sediments (Dickens and Owen, 1999; Gupta et al., 2004), and wind-blown dust increased in the North Pacific (Rea et al., 1998). This geographical range of events begs the question whether changes in Asia’s orography influenced global climate patterns, or global climate change affected the climate in the Himalaya, Tibet and adjacent regions.

There is another aspect to the 8 Ma palaeoclimate record that needs to be addressed. Much of the published evidence relates to increased seasonality and/or increased aridity at this time (Table 1). Not so many data point to increased overall precipitation. Several lines of evidence suggest the strengthening of the East Asian winter monsoon and weakening of the summer monsoon across northern and eastern China (e.g. Wan et al., 2007), consistent with a trend towards increased aridity over much of China. This is surprising, as so much of the modern monsoon impact on South and East Asia is through high precipitation and its effects on the landscape. The late Miocene decline in sedimentation rates across South and East Asia is likewise difficult to explain in terms of late Miocene monsoon enhancement, if that enhancement should mean increased precipitation (Clift and Gaedicke, 2002; Clift et al., 2008). It is also notable that recent studies of palaeoclimate and palaeoaltitude within the interior of Tibet are concluding that altitudes were similar to the present and climate was similar to the present since the late Miocene or earlier (Fig. 1; DeCelles et al., 2007; Saylor et al., 2009).

The spatial separation of the ITCZ and the Himalaya/Tibet may provide an explanation for the climatic and depositional patterns through the Miocene (Figs 3 and 4). Fig. 3 shows the increase in the latitudinal separation of the Central Pacific ITCZ and the Himalaya increased by roughly 1500-1900 km by the late Miocene, compared with the early Miocene. It is possible that the increasing separation of the ITCZ and the Himalaya led to a more seasonal and arid climate, as the ITCZ was only moved northwards for a few months of the year, leading to heavy summer monsoon rains and a relatively arid winter monsoon climate south of the Himalaya (like the modern case; Fig. 2) and a more arid subtropical climate generally across north and east China. The southward movement of the descending limb of the Hadley cell is also important in controlling climatic shifts: as the mean ITCZ position moved south through the Miocene, so presumably did each Hadley cell to its north and south, bringing drier winter climates to regions such as the Himalayan foreland. This climatic evolution is summarised on Fig. 4.

The explanation for the late Cenozoic variation in the latitude of the ITCZ is likely to be the emergence of a bipolar world (Miller et al., 1991; Rea, 1994; Zachos et al., 2001), as increased northern hemisphere glaciation produced hemispheric wind systems that were closer to mirror images of each other. The mean position of the modern ITCZ some 6 degrees north of the equator is a consequence of the greater size of the Antarctic ice sheet than its Arctic counterpart. Pre-Pleistocene climates had more a northerly ITCZ, caused by the greater asymmetry between the north and south polar regions and the lesser strength of northern hemisphere wind systems. A world lacking ice sheets at either pole would likewise have an ITCZ located nearer the equator.

There is no step-change in the separation of the ITCZ and the Himalaya in the late Miocene, at least not in available data (Fig. 3). One possibility is that a threshold was crossed in the climate system, such that an incremental increase in the ITCZ/Himalayan separation caused a climate re-organisation. Another possibility is that the increased latitudinal separation acted in concert with global trends towards a cooler late Cenozoic climate, but there is no clear shift in the global oceanic $\delta^{18}O$ proxy at this specific time (Zachos et al., 2001). Either way, we propose that the 8 Ma climatic shifts be regarded as the intensification of the both the South and East Asian monsoon's seasonal aspect, but a decline in terms of precipitation rates.

Our emphasis in this paper and Armstrong and Allen (2011) has been on the effect of the distance between the mean ITCZ and the Himalaya in terms of climate. It is worth remembering the tectonic changes in the Himalaya and southern Tibet through the Miocene, as over the middle Miocene the regime changed from the synchronous ductile shear along the MCT and STDS, with co-eval leucogranite generation and rapid exhumation, to the pattern of ~north-south normal faulting in southern Tibet and thrusting along the MBT and MFT that continues to the present day. As more age constraints are published the time gap between these contrasting styles reduces: the existing data suggest that at least a modest overlap of no more than a few million years on the scale of the entire orogen (Blisniuk et al., 2001; Searle et al., 2003; Harris, 2007), but in each individual area ~east-west extension postdates the top-to-north extensional shear along the STDS (Leloup et al., 2010).

We speculate that the reduction in precipitation over the Himalaya, driven by southwards ITCZ migration, may have played a role in thrust migration in the Himalaya. The mid Miocene saw a reconfiguration of the Himalaya, with new thrusting (MBT) breaking to the south of the MCT (e.g. Meigs et al., 1995). Previous models have made a link between the changing tectonics in southern Tibet and the reorganisation of thrusting in the Himalaya, with Tibetan surface uplift (suggested to be driven by lower lithosphere detachment) driving the migration of Himalayan thrusting southwards so as to re-establish a critically-tapered orogenic wedge (Harrison et al., 1992; Huyghe et al., 2001). The lack of identified surface uplift within southern Tibet, of the right age, is a problem for this model, as discussed above. However, it is possible that thrust migration was at least a partial response to changing Himalayan climate, and a represented a shift to a drier, wider, orogenic belt (e.g. Jamieson and Beaumont, 1988; Whipple and Meade, 2006).

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Figure captions

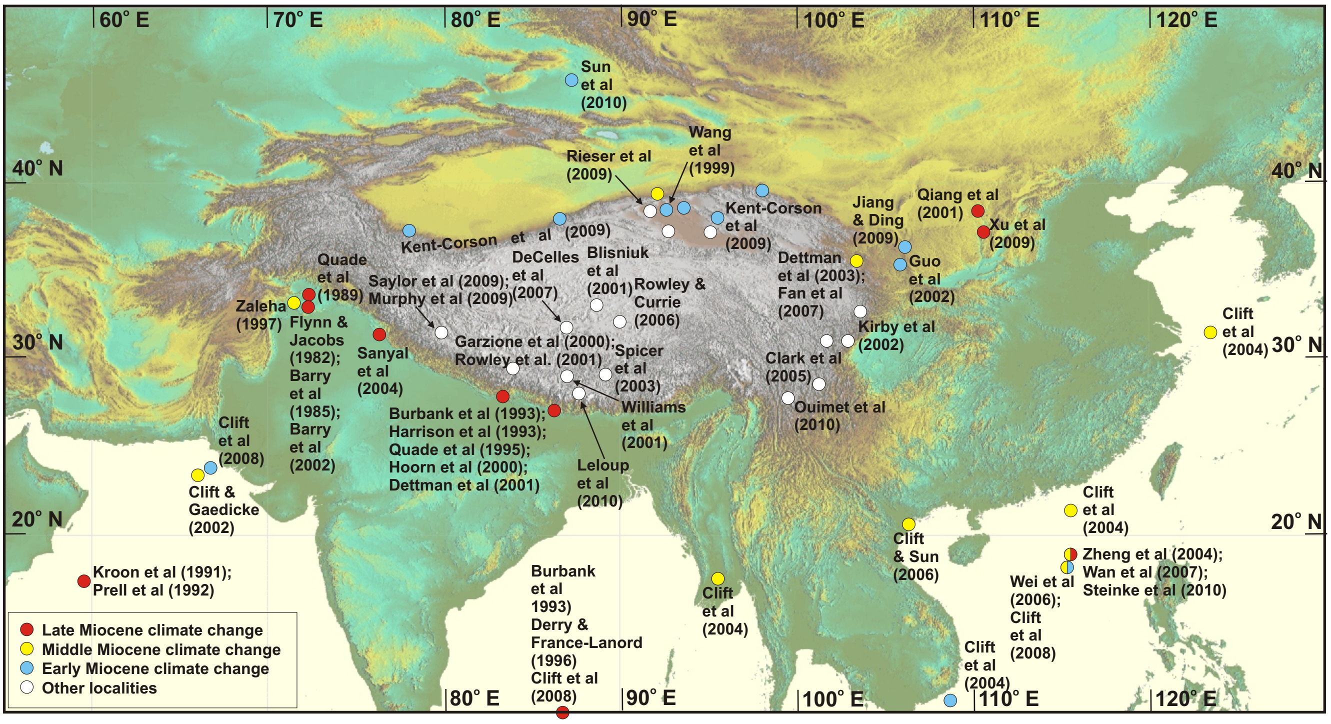
Fig. 1. A. Compilation of localities relevant to Miocene climate change, and/or the palaeoaltitude history of Tibet. See text for discussion. B. Geographic areas mentioned in the text.

Fig. 2. Modern seasonal behaviour of the ITCZ. Modified from Kalnay et al. (1996) as represented on http://geography.uoregon.edu/envchange/clim_animations/index.html (accessed 6.9.2010). Global topographic base map from http://www.ngdc.noaa.gov/mgg/topo/globega2.html (accessed 16.9.2010). Boxes show ITCZ study areas of Lyle et al. (2002) and Kim et al (2006).

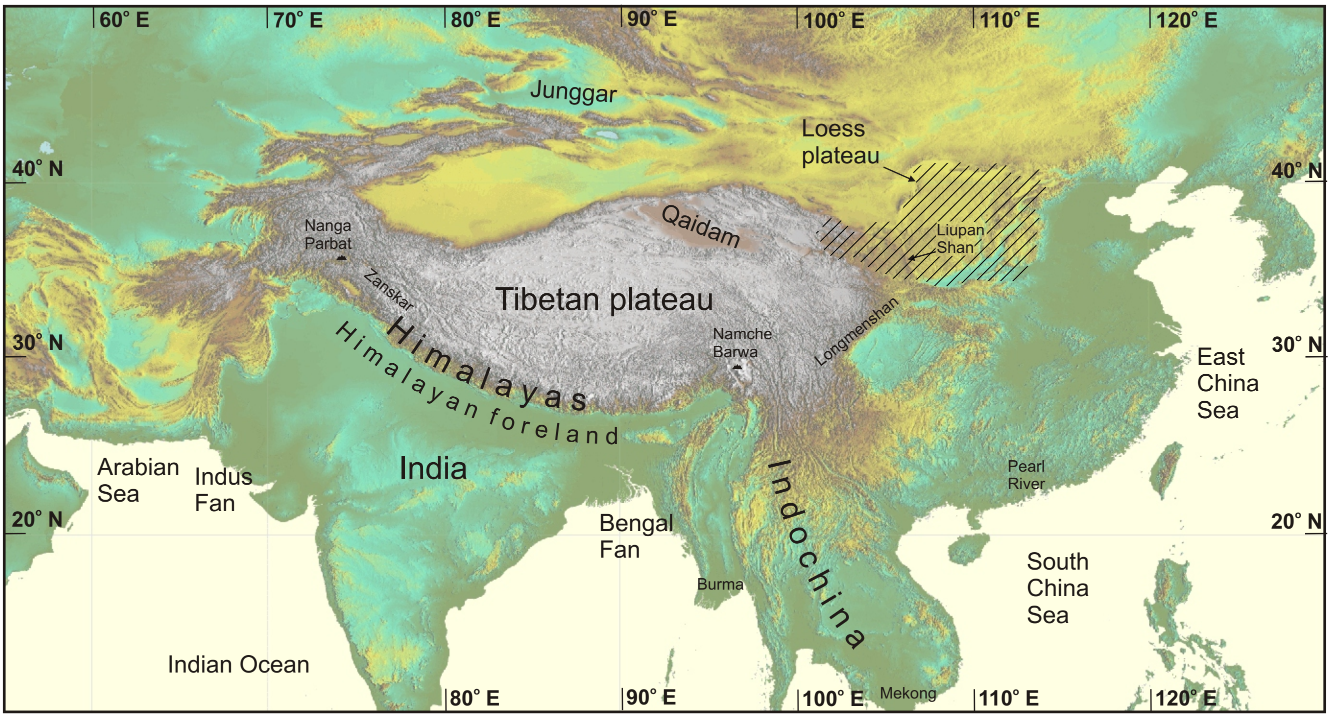
Fig. 3. Correlation of global isotopic data and Asian tectonics and climatic events, and the reconstructed positions of the Himalaya and the ITCZ for the past 35 million years. A. Isotopic synthesis for the past 35 million years. Global deep sea oxygen isotope records are from Miller et al., (1987; 2005) and Zachos et al. (2001). Seawater strontium isotope records from Richter et al. (1992). Vertical lines delimiting ice sheet state are from Miller et al. (2005). Abbreviations: MMCO, Mid-Miocene Climate Optimum; Mi-1, glaciation during oxygen isotope excursion Mi-1; Oi-1, glaciation during oxygen isotope excursion Oi-1; P-P, Pliocene-Pleistocene. B. Asian tectonic and climatic events summarised from sources discussed in the text. C. Reconstructed trajectories of the ITCZ. Black dots are from ODP Leg 199 (Lyle et al., 2002); open squares are from Kim et al. (2006). NW and NE Himalayan trajectories (open circles) are re-calculated from Molnar and Stock (2009) by moving their Pakistan and Bangladesh (stable Indian plate) reference points 500 km northwards to the Himalaya. Palaeogeographic errors fall within the open circle or are expressed as bars. Adapted from Armstrong and Allen (2011).

Fig. 4. Conceptual diagrams for ITCZ evolution and the Himalayan/Tibetan system through the late Cenozoic. Location of the Himalaya/S. Tibet is generalised to a position of the central part of the range: Present day = 30^{o} N; 8 Ma approximately 25^{o} N; 20 Ma approximately 20^{o} N.

Figure



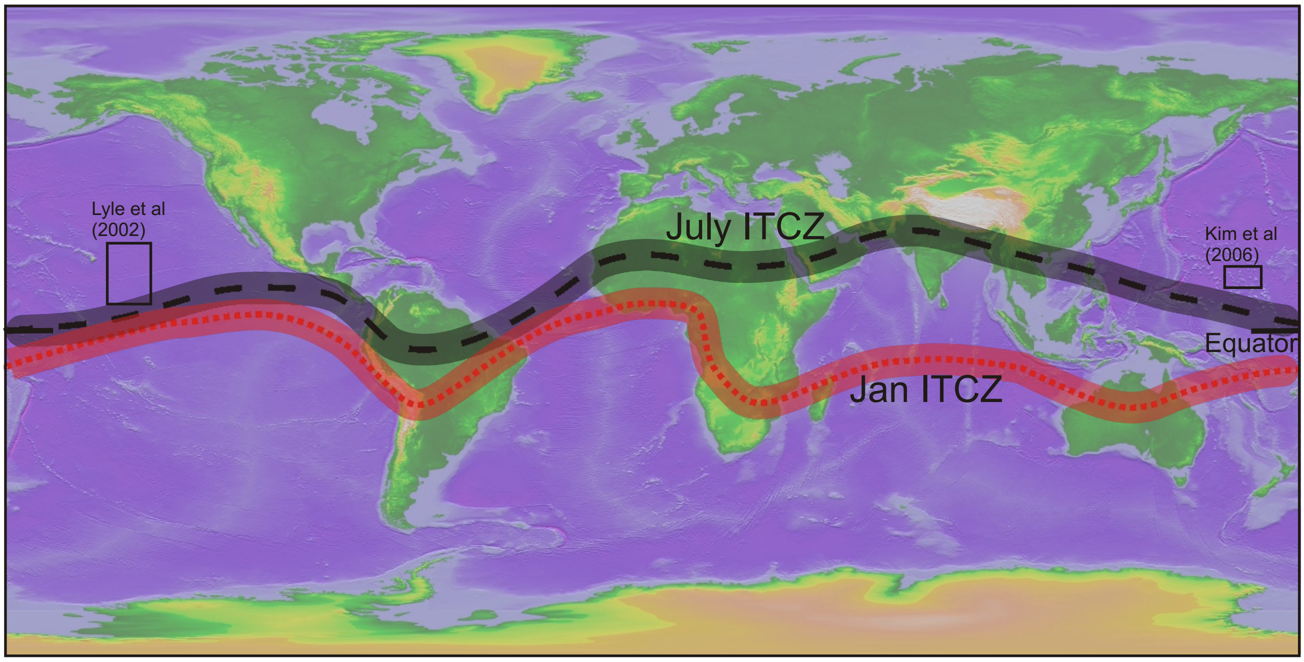
A.



B.

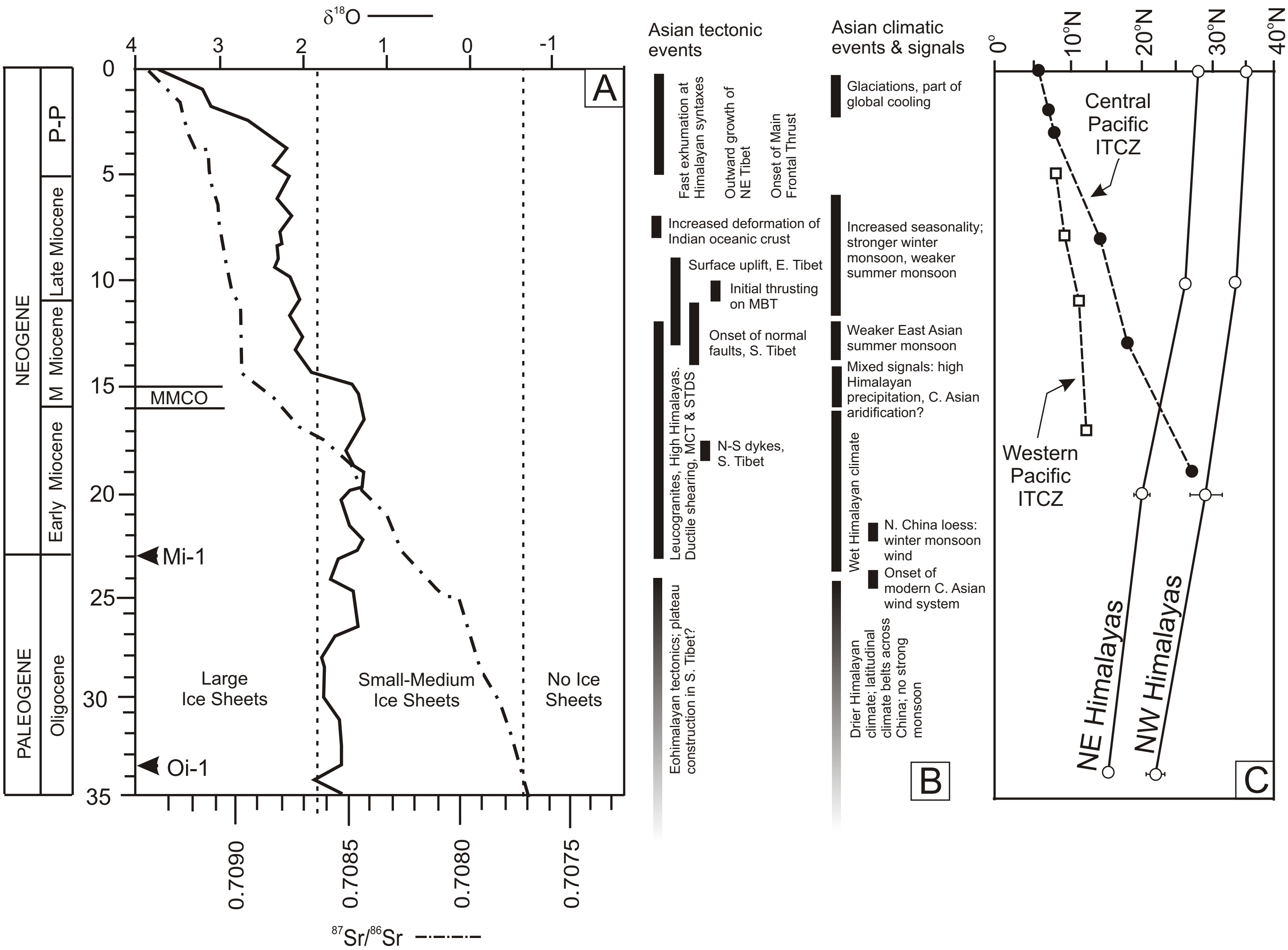
Allen & Armstrong Figure 1

Figure



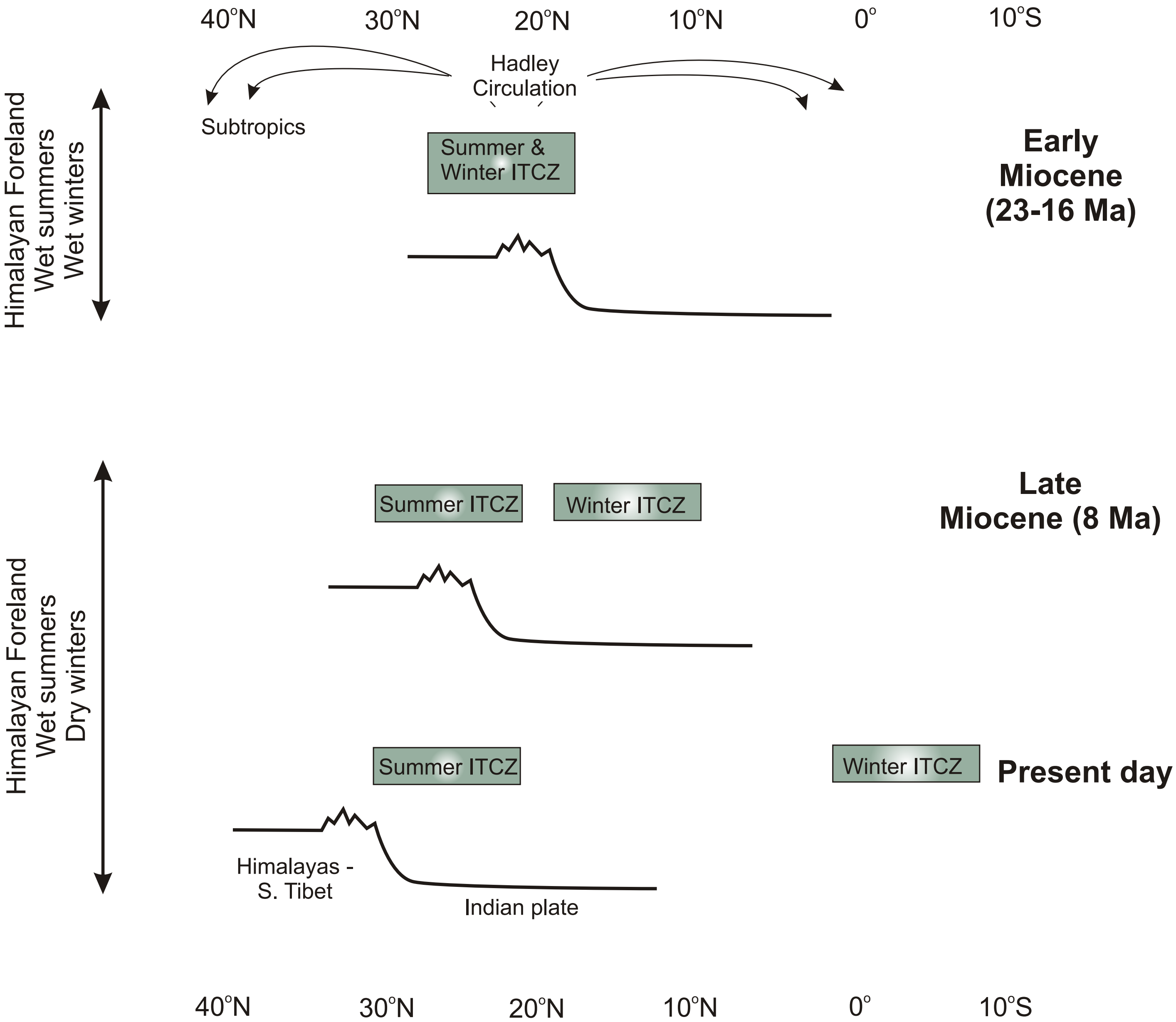
Allen & Armstrong Figure 2

Figure



Allen & Armstrong Figure 3

Figure



Allen & Armstrong Figure 4

Table

Table 1. Evidence for Miocene climate change in South, Central and East Asia.

Reference	Region	Timing (Ma)	Inferred climate change	Evidence
Quade et al (1995)	Southeast Nepal	7-6	Increased seasonality	Changes in soil carbonate $\delta^{18}O$ and $\delta^{13}C$
Harrison et al (1993)	Southeast Nepal	7	Increased seasonality	Changes in soil carbonate $\delta^{13}C$
Flynn and Jacobs (1982)	Northern Pakistan	7	Increased aridity	Vertebrate palaeontology
Barry et al (1985)	Northern Pakistan	7	Increased aridity	Vertebrate palaeontology
Galy et al (2010)	Bengal fan	7.4	Increased aridity?	Change in $\delta^{13}C$ of organic matter
Dettman et al (2001)	Southeast Nepal	7.5	Increased aridity	$\delta^{18}O$ trends in shells and mammal teeth
Steinke et al (2010)	South China Sea	7.5	Decreased summer monsoon intensity	Change in seawater $\delta^{18}O$
Hoorn et al (2001)	Southeast Nepal	8-6.5	Increased aridity?	Vegetation changes
Wan et al (2007)	South China Sea	8	Increased winter monsoon intensity	Chemical weathering proxies; sediment composition
Rea et al (1998)	North Pacific Ocean	8	Increased wind	Dust pulse
Zheng et al (2004)	South China Sea	8	Intensified winter monsoon wind	Foraminifera trends/productivity shifts
Kroon et al (1991)	Arabian Sea	8	Summer monsoon wind	Increase in Globigerina bulloides
Prell et al (1992)	Arabian Sea	8	Summer monsoon wind	Increase in Globigerina bulloides
Quade et al (1989)	Northern Pakistan	8	Increased seasonality	Changes in soil carbonate $\delta^{18}O$ and $\delta^{13}C$
Burbank et al (1993)	Bengal fan	8	Unclear – reduced glaciation?	Reduced sediment flux
Qiang et al (2001)	Northern China, loess plateau	8.35	Onset of monsoonal wind system	Onset of loess deposition
Wei et al (2006)	South China Sea	8.4	Increased winter monsoon intensity	Chemical weathering proxies; sediment composition
Fan et al (2007)	NE Tibet	9.6-8.5	Short-lived aridity	Sedimentary $\delta^{18}O$ excursion
Sanyal et al (2004)	Northern India	10-6	Increased seasonality	Changes in soil carbonate $\delta^{18}O$ and $\delta^{13}C$
Clift et al (2008)	Indus fan, Bengal fan, South China Sea	10-8	Weaker summer monsoon	Reduced sediment flux; chemical weathering indices
Barry et al (2002)	Northern Pakistan	10.1-9	Increased seasonality and aridity	Changes in fluvial sedimentology; vertebrate palaeontology
Xu et al (2009)	Northern China, loess plateau	11	Onset of monsoonal wind system	Onset of loess deposition
Jiang and Ding (2010)	Northern China	12	Stronger winter monsoon, weaker summer monsoon	Increase in 10-70 μm grain-size fraction
Dettman et al (2003)	NE Tibet	12	Increased aridity (Tibetan rain shadow?)	Increase in lacustrine carbonate $\delta^{18}O$
Jiang and Ding (2009)	China	14.25-11.35	Weaker summer monsoon	Pollen assemblage shift
Zaleha (1997)	Northern Pakistan	15-9	Strong seasonality	Variations in paleosols
Wan et al (2007)	South China Sea/SE China	15	Stronger winter monsoon; increased aridity	Chemical weathering proxies; sediment composition
Clift et al (2004)	East China Sea/NE China, South China Sea/SE China, Burma	~15	Stronger monsoon (increased precipitation)	High sediment flux
Wei et al (2006)	South China Sea/SE China	15.7	Stronger winter monsoon; increased aridity	Chemical weathering proxies; sediment composition
Clift and Gaedicke (2002)	Arabian Sea, Indus fan	16-11	Stronger monsoon (increased precipitation)	High sediment flux
Clift et al (2008)	Indus fan, Bengal fan, South China Sea	16-11	Stronger monsoon (increased precipitation)	High sediment flux; chemical weathering proxies
Jiang and Ding (2009)	Northern China, loess plateau	20.13-14.25	Humid climate	Pollen assemblages
Guo et al (2002)	Northern China, loess plateau	22	Onset of monsoonal wind system	Onset of loess deposition
Kent-Corson et al (2009)	Northern Tibet, Qaidam Basin	<~23	Aridification	Increase in sedimentary $\delta^{18}O$
Sun and Wang (2005)	China	~23	Stronger East Asian monsoon	Shifts in floral types and ranges
Wang et al (1999)	Qaidam Basin, northern China	~23	Shift to more humid climate	Decrease in xerophyte pollen
Clift et al (2004)	Mekong Delta	~23	Increased precipitation	Increased sediment flux
Wei et al (2006)	South China Sea	24-10	Increased precipitation	Increased chemical weathering
Clift et al (2008)	South China Sea	24-10	Increased precipitation	Increased chemical weathering
Sun et al (2010)	Junggar Basin, northern China	24	Aridification; change to modern wind patterns	Onset of aeolian deposition

*Research Highlights

Palaeolatitudes of the Pacific ITCZ and the Himalayas diverged through the Miocene

Himalayan climate changed to the modern South Asian monsoon in the Late Miocene

Himalayan tectonics may have adjusted to lower precipitation in the Late Miocene